THE ROLE OF R22 IN REFRIGERATING AND AIR CONDITIONING EQUIPMENT

David A. Didion
Leader of Thermal Machinery Group, Center for Building Technology,
U.S. National Institute of Standards and Technology.
U.S.National Committee, International Institute of Refrigeration.

Raymond Cohen
Purdue University, Director of the Ray W. Herrick Laboratories,
Professor of Mechanical Engineering, Purdue University.
Vice-chairman, U.S.National Committee,
International Institute of Refrigeration.

David R. Tree
Professor of Mechanical Engineering, Purdue University.
Editor, International Journal of Refrigeration.
U.S.National Committee, International Institute of Refrigeration.

1. INTRODUCTION

The United States government and refrigeration industry supports the Montreal Protocol as a reasonable approach to the CFC portion of the ozone problem. Both of these constituencies also support strengthening the Montreal Protocol to completely eliminate production of fully halogenated chlorofluorocarbons (CFCs). However, it is generally agreed in the U.S. that the phase out must occur in concert with an orderly transition to alternative refrigerants and refrigeration equipment with less ozone depletion potential (ODP). These alternate refrigerants will be principally hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). These two classes of refrigerant are considered to be essential to the interim solution to the ozone crisis.

In developed countries, virtually everyone is dependent on mechanical air conditioning and refrigeration to sustain their modern life style. Chilling of food during shipment and storage, refrigeration of medical supplies, air conditioning of mainframe computers are but a few of the many essentials of our civilization that require refrigerants as the systems working fluid. Thus, an acceptable solution to the CFC/ozone problem requires continuous maintenance and growth of these and other such systems.

The U.S. Environmental Protection Agency has recently performed an analysis that shows the need for nearly 100% worldwide acceptance of total CFC phase out. The adoption of HFCs (for example R134a) and HCFCs (for example R123 and R22) alternatives, at least in the interim, is the only feasible means by which this schedule can be met. In the past four years, there has been more research for the adaption of R134a and R123 to R12 and R11 systems than ever in the history of the refrigeration industry. Refrigerant properties measurements, materials compatibility studies, and hardware and system design changes have been conducted worldwide with information exchanged between countries on almost a daily basis. Even so, some previously unforeseen problems persist so that the system design for virtually any application is not yet final, and for some applications system design solutions are not even in sight. Tried and proven R22 systems are being extended to temperature and capacity ranges beyond their usual application to fill in these gaps; for example, for food refrigeration systems. Manufacturers in developed countries need alternatives and strategies that they can depend on before investing in the development of new products and equipment necessary for the CFC phase out. It is not likely that industry will make the large investments necessary to produce new equipment until new refrigerants are proven acceptable and are known to be available in adequate quantity for use. Developing countries need viable alternatives to combat a natural reluctance to participate in the CFC phase out in their quest for an improved standard of living. They cannot afford the risk or economic impact of refrigeration systems that are unproven or not in adequate supply. Thus, the HCFC and HFC refrigerants represent the only interim solution known today.

In addition to being one of the important solutions to the CFC/ozone problem, in the U.S. R22 is currently the most widely used refrigerant machinery working fluid in existing systems. In fact, R22 is in more refrigerating units than those systems containing all of the CFCs together, by many times. This wide spread dependence brings about additional and more difficult technical as well as social problems. Furthermore, R22 represents a rather unique balance with an inherent refrigerant system design trade off between capacity and efficiency. Efficiency has a rather significant influence on the global warming potential (GWP) value of the refrigerant. This paper addresses two problems:

a. developing alternative refrigerants for R22, and

b. not having HCFCs in general and R22 in particular as replacements for CFC systems fully available for the next two decades.

2. TECHNICAL DIFFICULTIES WITH REPLACING R22

The number of fluids that may be developed for use as refrigerants is not infinite. In fact, it has been suggested in previous studies [1,2] that the potential number of fluids that could be developed to meet only the most essential refrigerant characteristics is rather limited. Some sixty years ago when the refrigeration industry was desperately trying to get away from the toxic and flammable refrigerants that were being used universally, a rather ingenious fundamental study was conducted. Dr. Thomas Midgley of the General Motor Corporation used the periodic chart to deduce that only eight elements are readily available to form molecules that could possibly be used as a refrigerant (figure 1). All others formed solids or were unstable or unlikely to combine with other elements. Of the molecules that could be formed from the eight elements many would be unacceptable because of the very toxic and flammable hazards they were trying to avoid. The result of Dr. Midgley's work led to chlorofluorocarbons used today. Two years ago, Dr. McLinden and Dr. Didion of the U.S. National Institute of Standards and Technology reaffirmed Midgley's work by searching a data bank of over 700 fluids used in industry today for many purposes in addition to refrigeration. Of those that fit even the most rudimentary refrigerant requirements, all were comprised only of Midgley's eight elements. From these elements the only chemical "families" that yield several candidates for refrigerant usage are the very flammable hydrocarbons and halocarbons which are used today as refrigerants. Others may exist (e.g. ammonia) but are difficult to be discovered by any systematic research program. It cannot be assured that they will be found and surely the researchers cannot be held to a time schedule for any success.

McLinden and Didion further illustrated that of the halocarbon family, the chlorofluorocarbons, which are the refrigerants used today, can be systematized, as shown in figure 2, to indicate certain basic characteristics depending on their elemental makeup. Too much hydrogen results in a flammable refrigerant (the limit being pure hydrogen, a hydrocarbon with primary function as a combustible fuel). Too much chlorine results in a toxic refrigerant. Too little hydrogen (i.e.: the limit being none, with a molecule of only carbon, chlorine and fluorine atoms is called fully halogenated) results in a molecule so stable that it will survive in the troposphere long enough to drift its way into the stratosphere where it will accumulate over many decades. And herein lies the key to the ozone depleting refrigerant. It is not just the existence of the chlorine atom, but also the lack of the hydrogen which gives it its long atmospheric life to allow it to reach the stratospheric ozone. For example, R12 has two chlorine atoms but no hydrogen with an atmospheric life of over 100 years and an ODP = 1.0; while R123, which also has two chlorine atoms but its one hydrogen atom causes it to breakup in the troposphere within one to four years. This molecular breakup then allows the chlorine to react in a region far from the ozone layer. Thus R123 has an ODP = 0.017. Within the "safe" zone of the triangle lies the leading alternatives (R123 and R134a) for the fully halogenated refrigerants and R22, all of which contain one hydrogen atom giving these molecules their short atmospheric life, yet not flammable.

Of those refrigerants of the halocarbon family currently thought to be the leading alternative candidates for the fully halogenated refrigerants, some compromises and/or changes in machinery systems and practices now seem necessary in all applications. Compromises, such as lower thermodynamic performance, almost surely will not be acceptable in retrofitting existing systems and may well make the overall environmental problem worse because of the increase in power requirements causing more CO_2 (a major global warming gas) to be generated at electric utility power plants. Hopefully, design changes in machinery systems will help mitigate any efficiency decreases that may occur. With the global warming problem superimposed on the ozone problem, even the "safe zone" of figure 2 may represent only an intermediate solution. As it is, R22 has an ODP of the same order as R123 (0.05 vs 0.018) and GWP of the same order as R134a (0.35 vs 0.27) (table 1). If this case is unacceptable, even on a intermediate basis, then virtually no alternative is known to exist for many refrigeration and air conditioning applications that have tens of millions of units produced annually worldwide, and tens of millions in existence in the U.S. alone. Therefore, it is necessary to solve the ozone problem first and then the global warming problem as soon as possible, thereafter. For this reason the U.S. refrigeration industry has been working to use R22 as an alternative to the fully halogenated R12 and R502 refrigerants in the low temperature range where R134a is proving to be unsatisfactory. For example, in refrigeration applications approaching -40°C where R134a has significantly poorer thermodynamic performance than R12 or R502, R22 systems are currently being developed as replacements [3]. Of course, it is <u>not</u> possible to simply substitute R22 (i.e.: as a "drop-in" refrigerant) within an existing hardware system. A second and possibly more important example of the value of R22 as part of the ozone depletion solution is the use of it in refrigerant mixtures. R134a lubricant solubility problems persist. Further, pressure ratios are too high for low temperature applications, which prevents R134a to be a "drop-in" replacement. DuPont Company has developed a ternary mixture of R152a/R124/R22 which closely approximates the R12 vapor pressure curve. This ternary offers a potential to be a rare case of a "drop-in" replacement as well as an alternative for new systems. In spite of the use of R22, the net ternary GWP is only 0.16 with an ODP of 0.03 which it was designed to achieve. Early tests indicate that the efficiency of this mixture is slightly higher than both R12 and R134a in the air conditioning and refrigeration temperature ranges which means, if it proves to be compatible with machinery systems, it will not only help the global warming problem, because of its own lower GWP, but also by reducing CO_2 emissions at electric utilities.

Finding an alternative fluid for R22 poses several problems of greater magnitude than those facing the fully halogenated refrigerant alternatives, particularly if a "drop-in" satisfactory for the millions of existing systems is desired. "Drop-in" refrigerants require very similar thermodynamic performance as those for which they are being substituted, and the primary indicator for the thermodynamics is the fluid's normal boiling point (NBP). Figure 3 illustrates how refrigerants of similar boiling points will have similar vapor pressure curves and can either be used as "drop-in" refrigerants or require minimal design changes at least from a thermodynamic viewpoint. Note the similarity of R12 and R11 to R134a and R123, their respective alternatives. It was known immediately from halogenated refrigerant property data banks that these fluids of similar boiling points to the fully halogenated ones existed [4]. Whereas it is known that they do <u>not</u> exist for R22 except possibly for R125, which has a greater GWP than R22 (0.58 vs 0.35) and R143a which is flammable and has a GWP of 0.74. Unless a mixture of chlorofluorocarbons can be developed, the search must begin outside the traditional family of refrigerants, which greatly diminishes the likelihood that any fluid, that is found to meet the thermodynamic requirements, will meet the health, safety, stability, materials compatibility, etc., requirements that are equally essential (table 2). Relaxing these requirements will either greatly diminish the reliability of the refrigeration systems or return the industry to the same position it was in 1930 on health and safety issues.

Mixing refrigerants to achieve a given set of properties (e.g. those needed to clone R22) involves some craft as well as much science. Extremely careful measurements are required to determine the effects of both inter- and intramolecular forces on the thermodynamic property values before accurate mixture properties can be known. The best thermodynamic possibility for developing an alternative "drop-in" mixture would be from components that have properties near those of R22 and should have respective boiling points on either side of R22's boiling point. Selection of components is not unlimited because if one of the component's critical point is below the condenser operating condition, that component will essentially remain in the vapor phase throughout the entire operating cycle. The lower the critical point, the more severe this problem becomes. Since a mixture's properties are approximately the weighted average of its component's properties, such a limitation on one side automatically limits how far selection can go on the other side (e.g.: it is doubtful that R123 would ever be a component in a mixture that would clone R22). Another bound on component selections is due to heat capacity, which is proportional to molecular weight and molecular complexity. Since R22 is a simple molecule, any component which is more complex is likely to require a reduction in weight, usually accomplished through the retention of hydrogen atoms tending to make the mixture flammable. All of this is not to say that developing a R22 "drop-in" alternative through mixtures is impossible but rather to point out that the process is fraught with limitations and difficulties and at this time no obvious solution is in sight.

Developing an alternative that would be applicable only for new systems relaxes some of the refrigerant requirements because compensating changes in machinery components, and system design are possible. Refrigerant selection always involves an inherent trade-off between volumetric capacity and efficiency (C.O.P.). If a system is to be designed around a higher pressure refrigerant (i.e.: saturation line falls to the left of R22's, in figure 3), the condenser pressure and the pressure ratio may become a problem as well as the fact that the operating cycle will probably be less efficient because it may be operating nearer to the critical point. If the new refrigerant is to the right of R22 the compressor pumping capacity will be less because the operating pressures are lower, requiring larger machinery components. For example, a R134a compressor would have to be approximately 50% larger than a R22 compressor to produce the same capacity for a residential heat pump application. These two refrigerants have similar latent heats, but the R134a has a lower suction pressure and thus lower density. This requirement for larger refrigerant mass flow rates may well be handled, with increased capital costs, by oversized compressors but for the indoor coil (i.e.: cooling mode evaporator or heating mode condenser) a choice of serious tradeoffs exist. If the refrigerant tube sizes and/or number (in parallel) remain the same, the increased pressure losses due to vapor velocity increases. This effect may well cancel any thermodynamic efficiency gain expected from the use of a lower pressure refrigerant. Redesign of the indoor coil will offer a choice of compromises associated with increased size and complexity, all of which result in increased capital costs and/or sacrifice in system performance. These choices are particularly difficult for the U.S. home replacement market which is expected to exceed the new home market sometime in the 1990's. Other U.S. residential heat pump problems, particularly lubricant solubility, are greatly intensified over other applications because of the widely varying evaporator conditions, typically -30°C to 10°C. Further, as is being learned from R134a experiences, chlorine free refrigerants, as yet, have no proven lubricant which is acceptable at low temperatures. Although these machinery system design problems may eventually be solvable, the manufacturers will be able to do so only on a slow methodical basis because this equipment is sold with 5 or 10 year warranties.

Ignoring current residential health and safety requirements, one interesting alternative for R22 is ammonia (NH_3). (This is ironic, since ammonia was one of the refrigerants the industry was trying to eliminate when it first developed the chlorofluorocarbon family.) As can be seen from figure 3 the vapor pressure curves of R22 and NH_3 are quite similar with the exception that ammonia's critical point is higher, implying an even better efficiency. However, the toxicity and flammability characteristics of ammonia are such that even if home space conditioning safety requirements were changed ammonia would still be required to remain outdoors. A secondary heat transfer fluid would be used to transfer the energy indoors. This secondary fluid loop would add considerable expense to the product cost, reduce reliability by introduction of a liquid pump, and reduce the system efficiency significantly because the compressor would be required to "lift" the refrigerant an additional 5 to 10°C. Even if such a system were acceptable from a liability viewpoint its performance characteristics would have to be determined in detail before feasibility would be known. Of course, with ammonia's incompatibility with copper alloys, this could never be an option as a "drop-in" alternative for existing systems.

Although the path to replace the U.S. R22 systems is fraught with major difficulties, it is not impossible. However, it is only possible over a long period of time and with major tradeoffs in system design. This is largely because of the dependency of the global warming impact on system efficiency. Both limit the alternative options and/or require significant hardware design changes. The sequence of events to effect these changes are: (1) determine the refrigerant alternative, measure its thermophysical properties, begin toxicity evaluation (5 years); (2) in cooperation with equipment manufacturers develop compressors and begin materials compatibility evaluations; (3) design heat pump or refrigeration systems to meet today's reliability and efficiency standards (the heat pumps have to meet new 1992 Federal Government levels of COP = 2.9, for the cooling mode and 1.9 for the heating mode). These steps are largely sequential requiring an estimated minimum of 10 years to complete from the time an alternative is identified to a first production model. But, of course, the time for identification of the alternative is totally uncertain.

3. SOCIOECONOMIC DIFFICULTIES WITH REPLACING R22

In addition to the technical difficulties with replacing R22, there are a myriad of socioeconomic difficulties that must be overcome, otherwise there can be grave consequences to the quality of life. These consequences are related, among others, to the critical role of mechanical refrigeration to the world's food, shelter, health care, energy efficiency, communications and transportation needs.

The magnitude of the socioeconomic consequences can be gauged by considering the situation in the U.S. Table 3 indicates the quantity of refrigerating systems in the U.S., some expected lifetimes of this equipment, and the refrigerants commonly used in this equipment. It is obvious that there is a large amount of air conditioning and refrigeration equipment in use in the U.S. that can be expected to be in use for a long time, much of it for 10 to 20 years. Most of this equipment uses R22, R502 and R12, where R22 is also the refrigerant of choice to replace R12 and R502 for many applications. In fact, R22 is the only known replacement available in a number of applications.

It is highly unlikely that a "drop-in" replacement for R22 will be found. Even if a replacement would be found which can not be used with existing hardware systems, new refrigeration equipment will be required. Implementation, in this case, will take seven to ten years due to compressor and other equipment development time, manufacturing plant changes, technician and installer training, etc.

It is estimated that it could take as much as six billion U.S. dollars over the next decade for CFC producers to convert to HCFC and HFC refrigerants production [7]. While sizable, this investment is quite small when compared to the subsequent capital investment potentially necessary to produce the newly designed equipment to use these CFC substitutes. For example, in the U.S. alone, over 135 billion U.S. dollars in installed capital equipment is dependent on CFCs. The cost to replace similar equipment on a global scale is certainly a staggering amount. Although it may be necessary to make these investments eventually, the socioeconomic upheaval to do so rapidly is indeed grave. In light of the opportunity that HCFCs and HFCs present for the necessary balance between ozone depletion and global warming potentials and other refrigerant choice criteria, a well planned, probably slow, deliberate pace for conversion to HCFCs and HFCs is necessary.

Certainly several non-fluorocarbon substitutes were used prior to the development of CFCs for refrigerating systems. Generally, these substitutes are flammable and/or toxic. Injuries resulting from their use played a big role in the impetus for the development of the CFCs. Except for a few cases, in the U.S., the highly negative qualities of these substitute refrigerants are likely to impede progress toward their becoming a significantly large replacement alternative. For example, ammonia, which is both toxic and flammable, is acceptable in most societies only in large commercial or industrial refrigeration applications. It is not likely to be allowed in U.S. household applications unless a secondary heat transfer fluid were to be used to keep the ammonia outside the homes. The use of this secondary heat transfer fluid would certainly lower system efficiency due to secondary heat transfer effects, increased pumping losses, etc. Such loss in efficiency would, in turn, have a deleterious effect on the global warming problem. Even if the legal problems which limit the use of flammable and toxic refrigerants are overcome, it will take considerable time to train the many U.S. installers, service technicians, and the general public for the proper handling and use of these materials in homes as well as commercial buildings. Were these materials to become used in quantity, the training of installers and service personnel who will be required to work with these substances on a daily basis will be a large problem lest these personnel are put inappropriately at risk. Safety of these personnel and the public, liability, reliability, warranties of equipment, education, etc. will all require time for solution.

Another issue which must be mentioned is that of reclaiming and recycling refrigerants which are or will be put into use. We know, for example, that a large amount of the refrigerant used in chiller applications (perhaps 50%) is lost during the life time of the chillers. To correct this problem, one manufacturer, at least, has designed chiller equipment that incorporates self-contained systems to retrieve refrigerant. The problem is even worse in grocery store refrigeration equipment because of the very long refrigerant lines to and from the showcases. During the lifetime of this equipment, in the past many times more than the original charge of the systems could be released to the atmosphere. Education of service personnel, provision of reclaim and recycle equipment, and education of the public to require proper procedures is an absolutely necessary part of the solution to the ozone depletion and global warming problems.

The technical and socioeconomic problems discussed point to the need for global use of R22 and other HCFCs and HFCs as an interim substitute for CFCs. Until better substitutes are found, they provide the best balance between ozone depletion potential, global warming potential, and the other problems related to the choice of refrigerants. Wide acceptance and use of HCFCs and HFCs can reduce global warming and ozone depletion problems.

Studies in the U.S. [7] have been made which predict the chlorine in the ozone layer and the contribution to global warming from products using CFCs, HCFCs and HFCs. Figures 4, 5 and 6 show the results of these predictions for various assumptions regarding the use of these refrigerants. The effect of chlorine in the ozone layer from products which currently use CFCs is shown in figure 4. In case (1) it is assumed that all currently available options are adopted worldwide which will meet essential needs while protecting the environment through a conversion away from the use of CFCs as soon as possible but not later than the year 2000. These options include conversion to non-fluorocarbon substitutes where possible, increased conservation of CFCs and substitute refrigerants, and conversion of the remaining uses of CFCs to HCFCs and HFCs currently under development.

Case (2) is based on the same assumptions as case (1) except that HCFCs are <u>not</u> allowed to be used as replacement compounds for CFCs. Society continues to meet essential needs until new technologies are identified and developed. Fifteen years are assumed to be needed for identification of these technologies and an additional ten years is needed for development transitions period. The results show that atmospheric chlorine is minimized over the period reported by using currently identified alternatives to the CFCs: the HCFCs including R22. Uncertainties in projecting consumption of goods and services beyond 2030 makes projections beyond too uncertain.

Total atmospheric chlorine that can reach the ozone layer as a result of emissions from products using CFCs is shown for five cases in figure 5. Case (1) is a "worst case" based on the assumption that there is no restriction on the use of CFCs to meet the growing demand for them.

Cases (2) through (5) are based on the assumptions that, in applications where conversions are possible, that they proceed as quickly as possible worldwide and are completed by year 2000. Case (2) indicates the reduction in chlorine with the use of non-fluorocarbon substitute for CFCs, principally in aerosols, some blowing agents and cleaning agents.

Case (3) shows the additional reductions due to good conservation practices including improvements in design of equipment, better maintenance, recovery and recycling of refrigerants.

Case (4) shows the additional reductions due to the substitution of HFCs where applicable in some of the remaining applications such as in automotive air conditioning.

Case (5) represents the elimination of the remaining CFCs by the substitution for them of HCFCs. Note that Case (5) of figure 5 is the same as Case (1) of figure 4.

Assuming that currently identified HCFC and HFC substitutes will meet current safety and application requirements, wide acceptance and use of these substitutes could minimize atmospheric chlorine and protect the ozone layer.

With respect to global warming, predictions have been made of the percentage contributions to global warming of CFCs, HCFCs and HFCs. These results are displayed on figure 6. Case (1) is based on the assumption that demand will continue to grow for the use of CFCs to meet societal needs and is allowed without restriction. Case (2) is based on the assumption of a worldwide phase out of CFCs as soon as possible but not later than the year 2000, using the same measures as reported for case (5) of figure 5 including use of HCFCs and HFCs where needed and possible. Curve (2a) shows the warming contribution due to the CFCs. The relatively flat curve is due to the slow decay of the CFCs in the atmosphere. Curve (2b) shows the warming contribution of both the residual CFCs and the contribution of the HCFCs and the HFCs. Thus the small area between the two curves (2a) and (2b) shows the warming contribution due to the use of these alternative compounds.

4. SUMMARY AND CONCLUSIONS

1. In order to achieve the phase out of the production of CFCs as mandated by the Montreal Protocol, a reclaiming and reprocessing program must be set into place, so that present refrigerating equipment can continue to be used for its normal lifetime.

2. In order to achieve the phase out schedule of the fully halogenated refrigerants, the U.S. refrigeration industry is relying on R22 as part of the solution to the ozone depletion problem.

3. Within the chemical families of known refrigerants it is known that no direct substitute for R22 currently exists that has better environmental compatibility.

4. Successfully cloning of 22 by mixing known refrigerants or searching outside traditional refrigerant families is a very uncertain process fraught with component selection limitations and engineering difficulties; it can not be relied upon as a possible solution for a "drop-in" alternative for existing systems.

5. Hardware system design changes to compensate for property differences between R22 and an alternative will be required and will involve considerable time, possibly a decade or more after the alternative is identified to achieve a full production stage.

6. The dependency of the U.S. on R22 systems and the technical difficulties involved dictate that for the next decade R22 should remain part of the ozone depletion solution, and that if necessary for global warming reasons a phase out could begin sometime after the year 2000, assuming an alternative is known, and its hardware systems are sufficiently developed to assure the equivalent performance and reliability of today's systems.

7. In order to comply with the Montreal protocol and still maintain the present standard of living:

   a. there should be no regulation of HCFCs, especially R22, until new refrigerants are developed and ready for the market place, and

   b. an active research and development program to produce atmospherically benign refrigerants must be vigorously pursued.

There are two key issues to this approach. One, the HCFCs are a vital part of the replacement of CFCs. Therefore, manufacturers must have a guarantee that these refrigerants will be available in quantities needed until new atmospherically benign refrigerants are developed and can be produced in sufficient quantities. Two, governments must provide financial help needed in the public research sector to support industry in this very expensive program of developing new refrigerant alternatives and machinery redesigns required to maintain energy efficient, atmospherically compatible refrigerant systems.

5. ACKNOWLEDGMENTS

The work associated with the development of this paper was partially supported by the Electric Power Research Institute, project No. RP2792-09 under the direction of Dr. Powell Joyner, the National Institute of Standards and Technology, and the Ray W. Herrick Laboratories, School of Mechanical Engineering at Purdue University.

6. REFERENCES

[1] Midgley, T., "From the Periodic Table to Production", Industry and Engineering Chemistry, Volume 29, pp. 241-244, 1937.

[2] McLinden, M. and Didion, D., "Quest for Alternatives", ASHRAE Journal, Volume 29, No. 12, pp. 32-42, 1987.

[3] Muir, E., "Commercial Refrigeration and CFCs", CFCs: Today's Options - Tomorrow's Solutions, Proceedings of ASHRAE's 1989 CFC Technology Conference, held at the National Institute of Standards and Technology, Gaithersburg, MD, September 1989; ASHRAE, Atlanta, GA 30329.

[4] Stacer et., al., Advances in Fluorine Chemistry, Appendix B, pp. 173-175, Butterworth, 1963.

[5] Didion, D. and Bivens, D., "The Role of Refrigerant Mixtures as Alternatives", CFCs: Today's Options - Tomorrow's Solutions, Proceedings of ASHRAE's 1989 CFC Technology Conference, held at the National Institute of Standards and Technology, Gaithersburg, MD, September 1989; ASHRAE, Atlanta, GA 30329.

[6] "Statement of the Air-Conditioning and Refrigeration Institute (ARI) on Depletion of the Stratospheric Ozone Layer and on H.R. 2699 (U.S. House of Representatives)", presented to the Subcommittee on Health and the Environment, Committee on Energy and Commerce, U.S. House of Representatives, January 25, 1990. ARI, 1501 Wilson Boulevard, Arlington, VA 22209-2403.

[7] Alliance for Responsible CFC Policy, 2011 Eye Street, N.W., Suite 500, Washington, D.C. 20006, "HCFCs and HFCs Provide the Balance", H-07263, April, 1989; also "Fluorocarbon/Ozone", DuPont Update, published by "Freon" Products Division, B-13221, Wilmington, DE 19898, August 1989, and distributed at the UNEP meeting, Nairobi, Kenya, 1989; also private communication with Mac McFarland of DuPont, "Freon" Products Division.

List of Figures and Tables

Number of Vacancies in Outer Shell

Shell	32	8	7	6	5	4	3	2	1	0
I									1 H	2 He
IIa			3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne
IIb			11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
IIIa			29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
IIIb			47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
IVa			79 Au	80 Hg	81 Ti	82 Pb	83 Bi	84 Po	85 At	86 Rn

Figure 1. Midgley's arrangement of periodic table

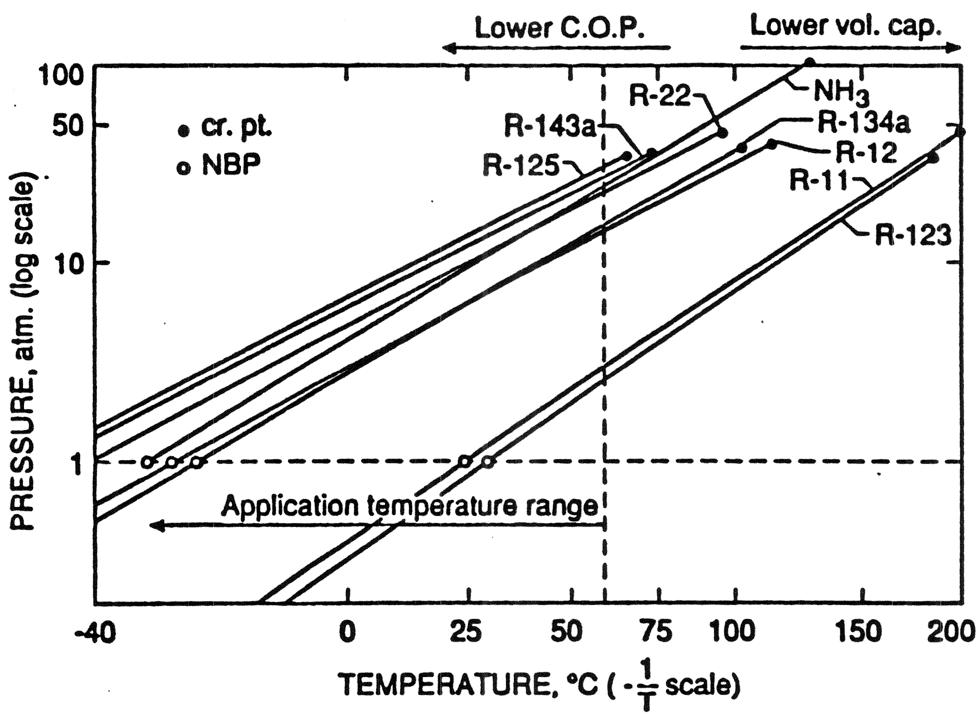

Figure 3. Pressure-Temperature diagram of selected refrigerants

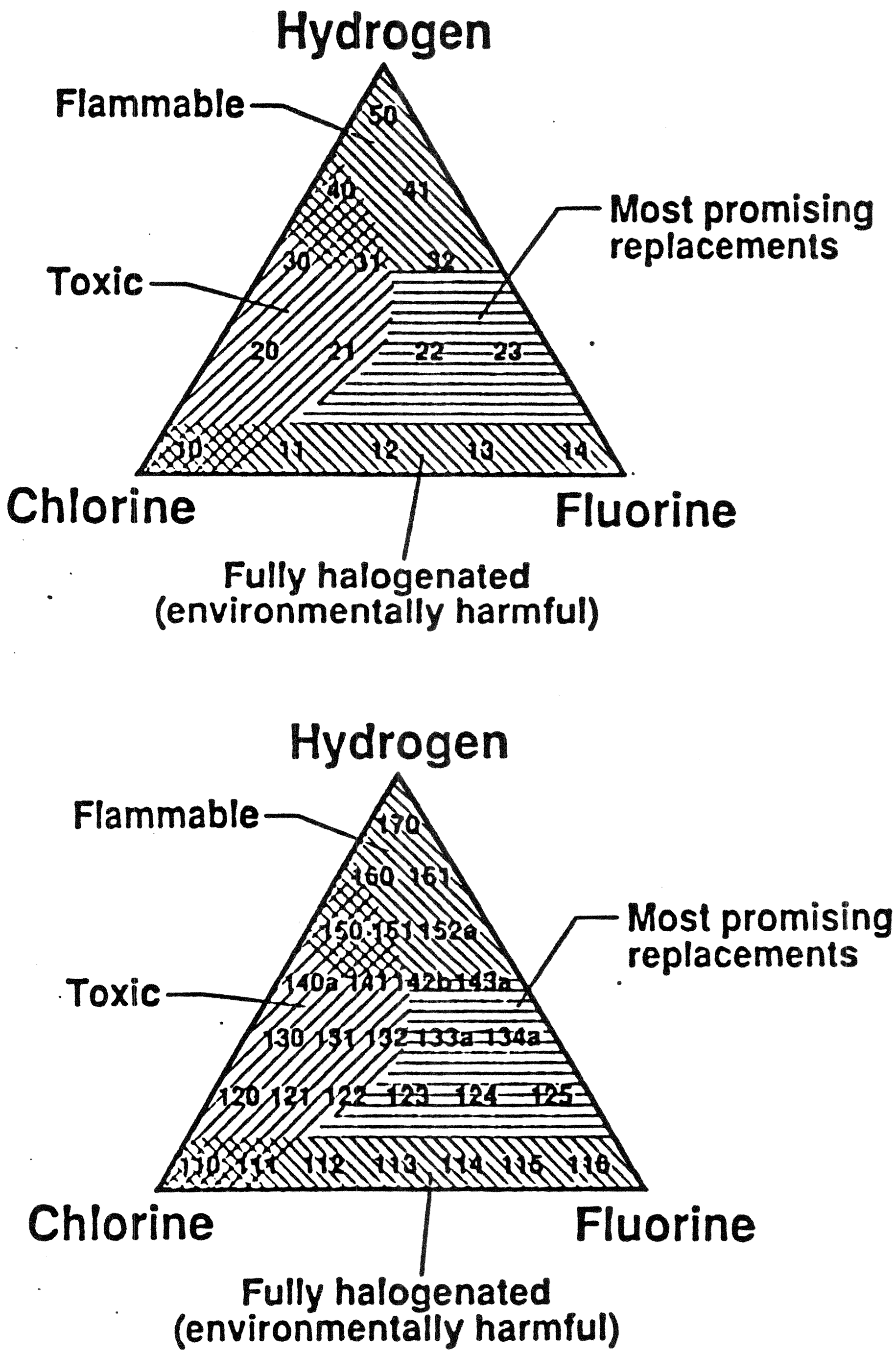

Figure 2. Tradeoffs among alternative CFC refrigerants

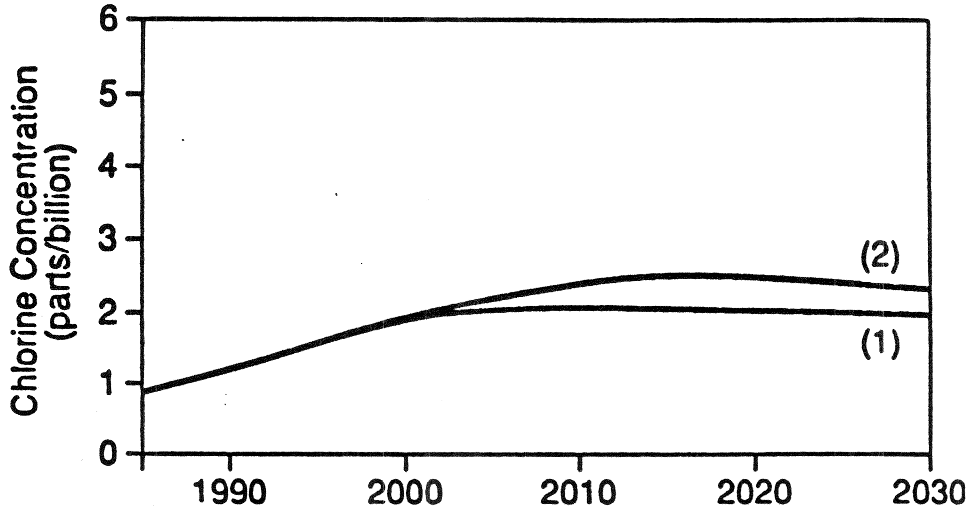

Figure 4. Difference in chlorine concentrations in the ozone layer due to the use of HCFCs

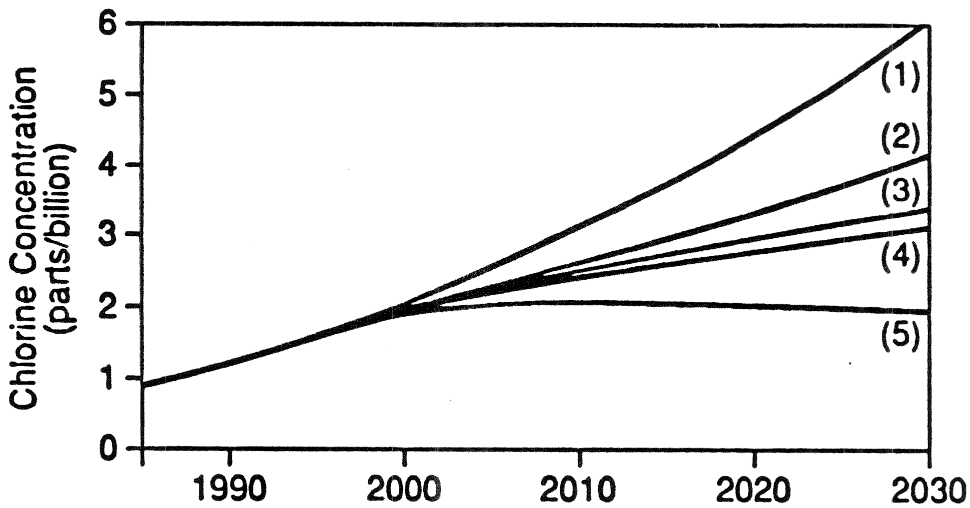

Figure 5. Difference in chlorine concentrations in the ozone layer due to various CFC restrictive measures

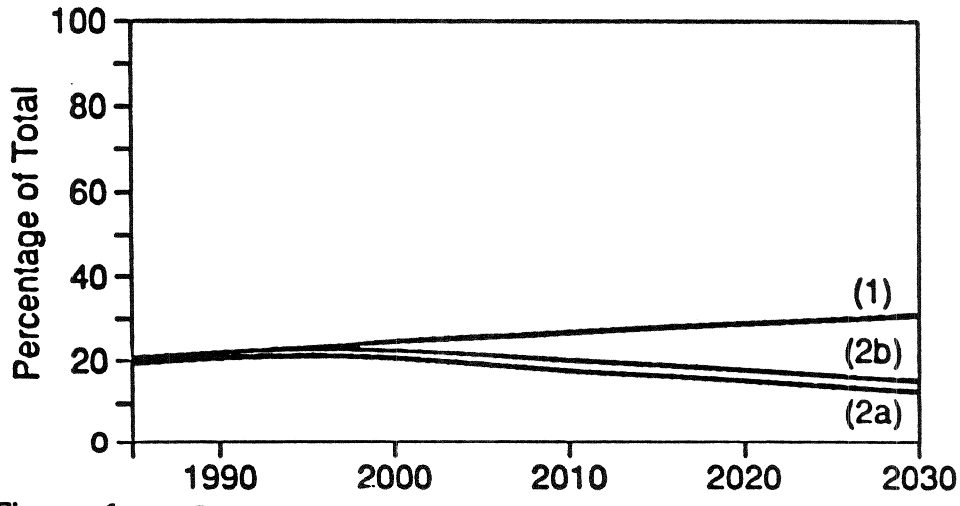

Figure 6. Fractional contribution of calculated global warming from products currently using CFCs

TABLE 1

Range of Ozone Depletion Potentials (ODPs)
and Global Warming Potentials (GWPs).
From NASA Panel for Scientific Assessment

Species	ODP	GWP
CFC-11	1.0	1.0*
CFC-12	0.9 - 1.0	2.8 - 3.4
CFC-113	0.8 - 0.5	1.3 - 1.4
CFC-114	0.6 - 0.8	3.7 - 4.1
CFC-115	0.3 - 0.5	7.4 - 7.6
HCFC-22	0.04 - 0.06	0.32 - 0.37
HCFC-123	0.013 - 0.022	0.017 - 0.020
HCFC-124	0.016 - 0.024	0.092 - 0.10
HCFC-125	0	0.51 - 0.65
HCFC-134a	0	0.24 - 0.29
HCFC-141b	0.07 - 0.11	0.084 - 0.097
HCFC-142b	0.05 - 0.06	0.34 - 0.39
HFC-143a	0	0.72 - 0.76
HFC-152a	0	0.026 - 0.033

* equivalent to 10^4 CO_2

Table 2

Refrigerant Selection Criteria

Science Issues:

Chemical	-	stable and inert
Health,	-	nontoxic (nonirritable)
Safety &	-	nonflammable
Environ.	-	does not degrade the atmosphere

Engineering Issues:

Thermal	-	critical point (boiling point) appropriate for the application
	-	low vapor heat capacity
	-	low freezing temperature
	-	favorable transport properties
Misc.	-	satisfactory oil solubility
	-	high dielectric strength of vapor
	-	reasonable containment materials
	-	easy leak detection
	-	low cost

TABLE 3

U.S. Refrigeration and Air Conditioning Equipment

<u>Equipment built by company members of the Air-Conditioning and Refrigeration Institute (ARI)</u>:

Residential central air-conditioning and heat pump units [6]:
- Over 4 million units shipped annually.
- Lifetime estimated at 15-25 years.
- Refrigerant: R22.

Centrifugal water chiller machines for air-conditioning large buildings [6]:
- 3000 to 4000 units produced per year.
- 80,000 to 90,000 units are installed.
- Lifetime estimated at 25-40 years.
- Refrigerants: R11, R12, R500 & R22.

Refrigeration equipment for supermarkets (R12, R22 & R502), restaurants (R12), trucks (R12 & R502), railroad cars (R12, R502 & R22) and other industrial equipment [6]:
- Two to four million units installed.
- Lifetime estimated at more than 15 years.
- Refrigerants: R12, R500, R502, R22 & ammonia.

Electric drinking water coolers [6]:
- Six to eight million units installed.
- Life time estimated at more than 10 years.
- Refrigerants: R12 and R500.

<u>Other Equipment</u>:

Automatic ice makers for hotels, restaurants and elsewhere:
- More than three million units installed.
- Life time estimated at more than 10 years.
- Refrigerants: R12 & R502.

Household refrigerators, reported by the Association of Home Appliance Manufacturers (AHAM):
- More than seven million household refrigerators shipped, and more than one million household freezers shipped in 1989.
- Lifetime estimated at more than 20 years.
- Refrigerant: R12.

Room air conditioners, reported by AHAM:
- More than five million units shipped in 1989.
- Lifetime estimated at more than 15 years.
- Refrigerant: R12 & R22.

Automobile air conditioners, supplied by the Motor Vehicle Manufacturers Association (MVMA):
- More than seven million automobiles with air conditioning shipped in 1988.
- Lifetime estimated at more than 5 years.
- Refrigerant: R12.